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TECHNOLOGY FOR THE CONTROL OF PARTICULATES AND SULFUR OXIDES BY ELECTROSTATIC TECHNIQUES

by
Edward B. Dismukes
John P. Gooch
Southern Research Institute
P. O. Box 55305
Birmingham, Alabama 35255-5305

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EPA Project Officer
Louis S. Hovis
Air and Energy Engineering Research Laboratory
U. S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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16. ABSTRACT The report summarizes research performed by Southern Research Institute on several aspects of the E-SOx Process, invented by EPA to jointly control particulate matter and SO2 in coal-fired boiler emissions by retrofitting an existing electrostatic precipitator (ESP), formerly used only for particulate removal. The report covers research on potential ESP sites for process application, process economics, characterization of process solid waste collected in the ESP, measurement and modeling of prechargers in the retrofitted ESP, and effectiveness of the process with respect to SO2 removal. Experiment results described in the report confirm original EPA laboratory work and were influential in the decision to proceed with a large pilot evaluation of E-SOx. Research emphasis was on ESP performance, under E-SOx conditions, to verify that this essential equipment process component could retain its primary function of particle removal at a level equal to removal prior to modifications necessary for E-SOx. Further research is suggested.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Coal	Pollution Control	13B	21D
Particles	Combustion	Stationary Sources	14G	21B
Sulfur Dioxide	Electrostatic Precipitators	E-SOx Process	07B	
Electrostatics		Particulate	20C	13I
Emission				
Boilers			13A	

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ABSTRACT

This report discusses research in various areas associated with the process for flue-gas clean-up known as E-SOX. The process is based upon 1) the injection of a spray of lime slurry in a chamber just before an electrostatic precipitator (ESP) to combine chemically with SO_2 and 2) the removal of E-SOX solids and fly ash simultaneously in the ESP.

Two of the research tasks performed were in the nature of survey and analysis. First, the population of ESPs in the utility industry that may provide for application of E-SOX was surveyed. Second, a technical and economic assessment of E-SOX was performed.

One of the areas of experimental investigation concerned the use of a cold-pipe precharger for enhancing particle charging in the E-SOX process. Measurements were made of the relationship between particle diameter and charge imparted in the precharger. The charging performance of the cold-pipe precharger was compared with that of a conventional ESP; the conclusion was that for E-SOX solids of low resistivity, which is to be expected as the rule, the precharger offers no clear advantage.

Another area of experimental study consisted of performing E-SOX experiments in a pilot-scale, coal-fired combustor rated for 1×10^6 Btu/h. These experiments yielded samples of E-SOX solids that were characterized by various techniques but used primarily in the study of electrical resistivity discussed below. Other experiments compared SO_2 removals by injection of slurries prepared either by mixing commercial hydrated lime with water or by simultaneously slaking quicklime and preparing a slurry therefrom. The slurry prepared from quicklime gave slightly better SO_2 removal.

The final experimental study led to the development of a laboratory method that yields repeatable data on the electrical resistivity of solids from the E-SOX process and other sorbent processes for SO_2 control, such as LIMB. The resistivities of separate compounds of calcium that are present in E-SOX and LIMB solids were determined. An effort was made to develop a method for predicting the resistivities of these solids, based primarily on the effects of the distinct calcium compounds, but the effort was not successful.

The experimental work was concluded before the field demonstration of E-SOX began. The demonstration, now in progress at Ohio Edison's Burger power station, is nevertheless discussed briefly at the conclusion of this report.

CONTENTS

Section		Page
Abstract		iii
1.	Introduction	1
2.	Survey of Electrostatic Precipitators in the Utility Industry	3
3.	Technical and Economic Analysis of the E-SOX Process	7
4.	Measurement and Modeling of the Performance of a Precharger	12
	Introduction	12
	Experimental Facility	12
	Experimental Results	14
	Mathematical Modeling	14
	Precharger versus Conventional ESP	19
	Reentrainment Emissions	21
5.	Revision of the Mathematical Model of Electrostatic Precipitation	22
6.	Studies of the E-SOX Process in a Pilot-Scale Combustor	24
7.	Measurement and Prediction of the Electrical Resistivity of Solids Produced by Processes for SO_2 Control	26
8.	Field Demonstration of the E-SOX Process	32
References		33
Appendix A.	Data Base of Electric Utility Plants for Use with E-SOX Program	A-1
Appendix B.	Quality Control Evaluation Report	B-1

FIGURES

Number		Page
2-1	Total generating capacity of all plants in data base for each range of SCA values	4
2-2	Total number of units in data base for each range of SCA values	5
2-3	Coal sulfur and generating capacity for each individual unit having an SCA between 175 and 200 $ft^2/(1000\ acfm)$	6
4-1	Top view of the cold-pipe precharger geometry	13
4-2	Millikan data obtained with the lowest precharger electrical operating point	16
4-3	Millikan data obtained with the intermediate precharger electrical operating point	17
4-4	Millikan data obtained with the highest precharger electrical operating point	18
4-5	Estimates of the distance and treatment time along a conventional ESP gas passage that are required to obtain the fly ash particle charge values achieved by the cold-pipe precharger	20
7-1	BET area as a function of annealing temperature in an atmosphere containing 10.4% humidity by volume. Circles are for the E-SOX sample; squares are for a LIMB sample	27
7-2	Resistivities of calcium compounds expected to be present in ash/sorbent mixtures	28
7-3	Comparison of the resistivities of an E-SOX sample, calcium hydroxide, and calcium sulfite	29
7-4	Comparison of the resistivities of 4 LIMB samples (17 and 18 with hydrated lime injection, 101 and 119 with limestone injection), calcium hydroxide, and calcium sulfate	30

TABLES

Number		Page
3-1	Precipitator performance with E-SOX	9
3-2	Cost summary for E-SOX	9
3-3	First year annualized costs of E-SOX ($1000/yr)	10
4-1	Summary of Millikan cell measurements of the charging of fly ash particles by a cold-pipe precharger	15

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James L. DuBard, a senior member of the staff of Southern Research Institute's Environmental Sciences Research Department, was responsible for planning and directing most of the research described in this report. Roderick Beittel, another senior member of the staff, also made major contributions. Both of these individuals have now left the Institute's employment. This report has been prepared in their absence by their former associates here.

David F. Becker of Gilbert/Commonwealth, Inc., working under a subcontract, made the principal contribution to the technical and economic assessment of E-SOX that is summarized in Section 3 of this report.

Ronald P. Young, who remains at Southern Research, is the author of the topical report on resistivity measurement and prediction that is summarized in Section 7 of this report.

SECTION 1

INTRODUCTION

This is the final report of research performed by Southern Research Institute under Cooperative Agreement No. CR-812282, which was entitled "Technology for the Control of Particulates and Sulfur Oxides by Electrostatic Techniques." The research was conducted during the period from August 1, 1985, to July 31, 1990.

The title of this report refers to E-SOX technology for the simultaneous control of particulate matter and sulfur oxides in a coal-burning electric power plant. The research performed under the cooperative agreement served as a bridge between the original development of the E-SOX technology in EPA laboratories and the pilot-scale testing of the technology that is currently in progress in mid-1990 at the Burger power station of Ohio Edison Company.

The E-SOX process for controlling sulfur oxides (mainly the dioxide) is based on the injection of a spray of an aqueous slurry of slaked lime at the inlet of an electrostatic precipitator (ESP). The SO_2 reacts with calcium hydroxide to produce calcium sulfite; the resulting solid reaction product, associated with part of the calcium hydroxide that does not react, is collected in the ESP along with fly ash from the boiler. In the initial concept of E-SOX (1), the electrical components would be removed from the first field of the ESP and replaced with the spray nozzles for the slurry. In the configuration of E-SOX at the Burger station, however, a separate spray chamber ahead of the ESP was employed.

The research performed at Southern Research consisted of the following tasks:

1. A survey of ESPs in the utility industry where the E-SOX process may find application.

2. An analysis of the technical and economic aspects of the E-SOX process. (Gilbert/Commonwealth, Inc., assisted in the performance of this task.)

3. The measurement and modeling of the performance of a precharger that can be incorporated in the E-SOX process.

4. The investigation of the E-SOX process using a pilot-scale combustion system.

5. The development of a measurement technique that is suitable for determining the electrical resistivity of E-SOX particulate matter and the development of a method for predicting the resistivity of solids from the E-SOX process and other sorbent processes for control of sulfur oxides.

This report presents only a summary of some of the areas of investigation. The results from several of the tasks have been published in earlier reports; since the details of the approaches taken and the data obtained are available elsewhere, they are not repeated here. References to the earlier reports are given at appropriate places in the body of this report.

SECTION 2

SURVEY OF ELECTROSTATIC PRECIPITATORS IN THE UTILITY INDUSTRY

A data base pertaining to ESPs in the utility industry was compiled to provide the basis for estimating the potential breadth of application of E-SOX technology. This data base was derived from a much broader data base that had been compiled by Burns and Roe for the Electric Power Research Institute under RP 1401; the earlier data base was provided for our use through the courtesy of EPRI. Certain restrictions in the breadth of the previously existing information were applied to identify the ESPs that are most relevant for E-SOX application. First, only cold-side ESPs burning Eastern bituminous coals were of interest. Second, each of the units was required to have a specific collecting area (SCA) between 100 and 400 ft^2/(1000 acfm). Finally, each was required to be associated with a boiler with a rated capacity of 50 MW or more and with a coal supply having a sulfur content greater than 1%.

The type and scope of information compiled are indicated in Figures 2-1 and 2-2. Figure 2-1 is a bar chart showing total generating capacity of all units in each range of SCA values, in increments of 25 ft^2/(1000 acfm). Figure 2-2 shows the total number of units for each increment in SCA.

The specific information compiled for each range of SCA values is illustrated in Figure 2-3. The sulfur content of the coal and the megawatt rating of the boiler are shown for each unit having a SCA value within the selected range of values (in this illustration, 175-200 ft^2/[1000 acfm]). The identity of each unit referred to in Figure 2-3 is given in the appendix of this report, which also contains the complete results of the survey.

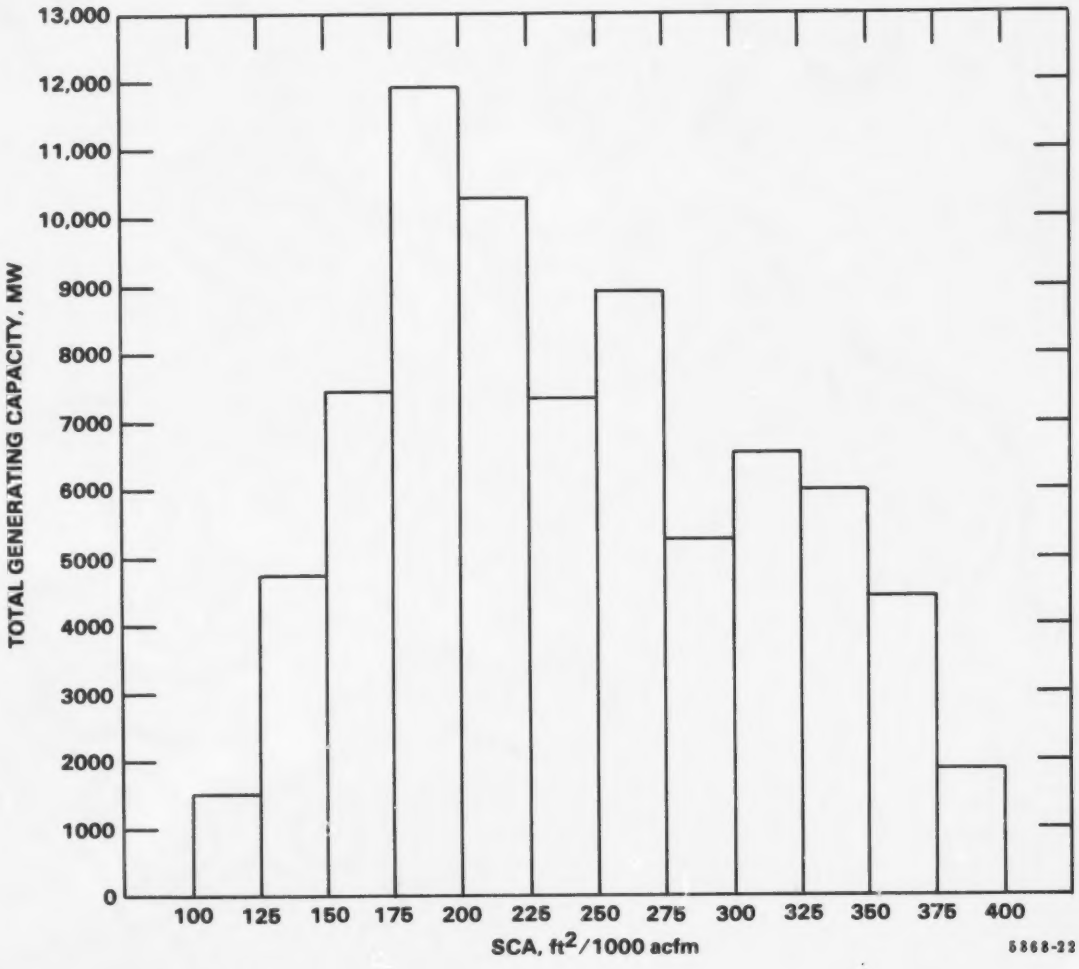

Figure 2-1. Total generating capacity of all plants in data base for each range of SCA values.

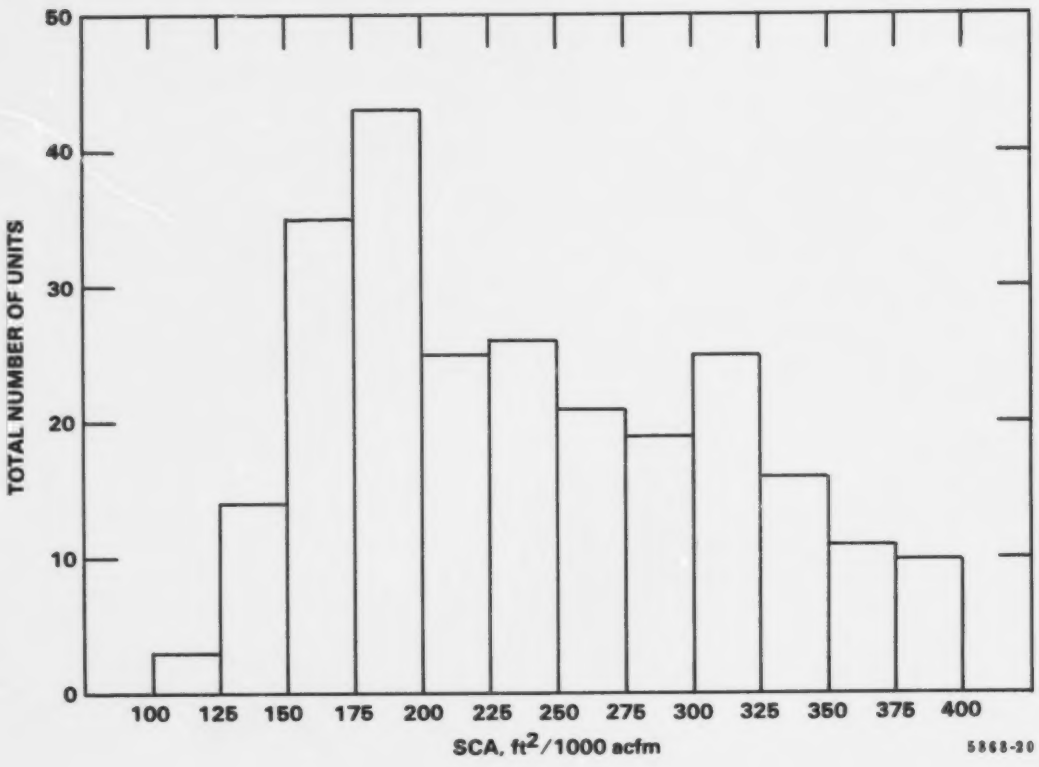

Figure 2-2. Total number of units in data base for each range of SCA values.

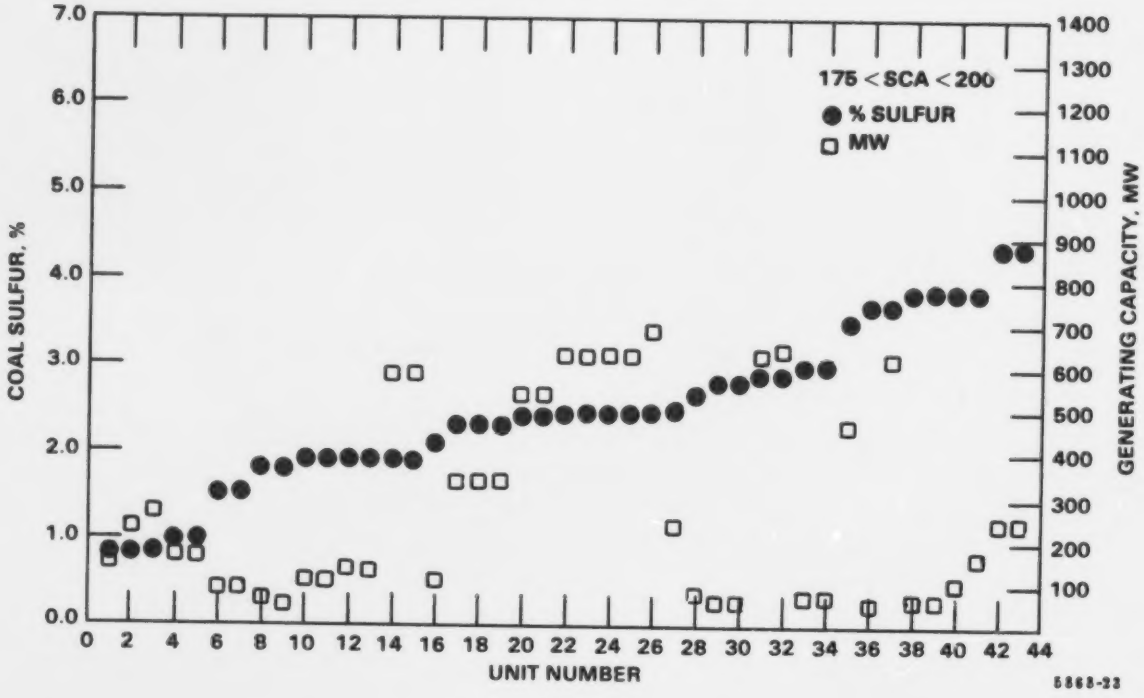

Figure 2-3. Coal sulfur and generating capacity for each individual unit having an SCA between 175 and 200 $ft^2/(1000\ acfm)$

SECTION 3

TECHNICAL AND ECONOMIC ANALYSIS OF THE E-SOX PROCESS

This analysis was performed jointly by Gilbert/Commonwealth, Inc. (G/C), and Southern Research Institute with G/C supported through a subcontract from Southern Research. The results of the analysis have been published as the following document (2):

> D. F. Becker and J. L. DuBard, Conceptual Designs and Cost Estimates for E-SOX Retrofits to Coal-Fired Utility Power Plants, EPA-600/7-87-028 (NTIS PB88-143995), U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, December 1987.

The following text is a repetition of the executive summary of the above report.

> Background. E-SOX technology has been proposed as a feasible means of lowering sulfur oxide emissions from power plants upon retrofit to an existing electrostatic precipitator. Accordingly, G/C performed a conceptual study to evaluate various retrofit situations. In so doing, applicable bases were kept identical with a similar study conducted in 1983 concerning Limestone Injection Multistage Burner (LIMB) systems (3).
>
> The conceptual designs discussed herein are based on a "generic" power plant. All subsystems necessary for a complete E-SOX system are included in the costs. Optimizations of equipment and systems were performed on a limited basis, as this is not a site-specific study. Thus, costs will vary from those presented here, as specific locations are considered. The study does provide a point of reference for comparison purposes, and shows where future research and development efforts should be concentrated.
>
> Scope and Approach. Following the LIMB study, plant size was selected as 500 MW, with existing particulate control equipment designed to meet the 1971 New Source Performance Standards for particulate matter. The process designs were based on lime stoichiometries and approach temperatures necessary to achieve 50% sulfur reduction for a typical Eastern, medium-sulfur (2.5%) bituminous coal. Two process conditions were selected using hydrated lime as a reagent, and one using quicklime. For one of the lime hydrate process conditions, four different precipitator upgrade configurations were evaluated. A total of six E-SOX cases were investigated. These are summarized below:
>
> > Case 1 — Hydrated lime reagent, Ca/S = 1.3, approach temperature 40 °F, original ESP with an SCA of 218 $ft^2/(1000\ acfm)$, retrofitted with precharger and large-diameter electrodes.

Case 2 — As Case 1 with the exceptions of no precharger, weighted wires instead of large-diameter discharge electrodes, and collecting plates 1.5 ft longer in each field.

Case 3 — As Case 1 with the exceptions of an original ESP with an SCA of 150 ft^2/(1000 acfm), plate height increased by 3 ft and collecting plates in each field increased in length by 1.5 ft.

Case 4 — As Case 3 with the exception of no precharger, weighted wires instead of large-diameter discharge electrodes, and an additional short third active field.

Case 5 — As Case 1 with the exceptions of a Ca/S ratio of 1.5 and an approach temperature of 50 °F.

Case 6 — As Case 1 with the exception that pebble quicklime is used as a reagent.

The study consisted of the conceptual equipment selection, equipment arrangement, and estimates for capital and first-year operating and maintenance costs for the E-SOX system and all supporting equipment in the above six cases.

Findings. The mechanical equipment used as a basis for these designs is predominantly commercial. Lime receiving and storage and slurry preparation are state-of-the-art for many existing scrubbers, both wet and dry. On the other hand, the two-fluid nozzle arrangement, because of its requirement for a relatively flat and fine droplet-size distribution (40-50 μm), requires some development work. Also some of the chosen precipitator modifications, which are advanced technology to achieve the required particulate removal, as exemplified by the precharger and large-diameter electrodes, require developmental work. Hence, there is more uncertainty in the precipitator performance of Cases 1, 3, 5, and 6 than in the Cases 2 and 4, which are more conventional ESP upgrades. Because there are limited laboratory-scale process data available, there are process uncertainties associated with reagent stoichiometry, approach temperature, and residence time. The latter also raises the question of whether adequate spray drying can occur without wetting the precipitator.

Concerning precipitator performance for the E-SOX process, computed ESP collection efficiency and particulate mass emissions are tabulated for each case in Table 3-1. ESP performance was assessed by Southern Research Institute using its ESP mathematical model (4). A comparison of Cases 1 and 2 shows that a modest increase in plate length will achieve the same ESP performance improvement as the installation of novel electrodes. With low-resistivity fly ash and reasonable plate area after an E-SOX retrofit (SCA of 173 ft^2/[1000 acfm] prior to ESP modifications), the precharger offers little performance advantage. It accomplishes quickly the dust particle charging that otherwise would be accomplished within 2 or 3 ft of travel along a conventional gas passage. The large-diameter discharge electrodes, on the other hand, offer a performance advantage due to the increased interelectrode electric field. In Cases 3 and 4, with a much lower plate area

after an E-SOX retrofit (SCA of 118 ft^2/[1000 acfm] prior to ESP modifications), a substantial reconstruction of the ESP is required to limit particulate emissions to 0.1 lb/10^6 Btu.

(Author's note: Later experience at the pilot-scale demonstration of E-SOX, referred to in Section 8, showed that there are serious reentrainment problems that the model does not predict and there are thus far more serious limitation in ESP performance than Table 3-1 suggests. Moreover, there is the possibility of a degradation of ESP performance due to the exceptionally high mass loading and fine particle size. As is well known, the particle-bound space charge can either improve collection efficiency by increasing the electric field strength near the plate or degrade efficiency by reducing the corona current, thereby affecting the rate of particle charging.)

TABLE 3-1

PRECIPITATOR PERFORMANCE WITH E-SOX

	Case No. 1	2	3	4	5	6
SCA (ft^2/100 ACFM)	173	201	163	148	171	172
Outlet Emissions, lb/10^6 Btu	0.08	0.08	0.08	0.07	0.08	0.08
Collection Efficiency, %	99.59	99.56	99.57	99.62	99.57	99.48

A summary of the capital and O&M costs for the six E-SOX cases is provided in Table 3-2. The capital costs compare very favorably with other retrofit SO_2 removal technologies. This is attributed to the maximum use of existing equipment and minimal new equipment requirements. First year O&M costs are largely influenced by lime consumption and delivered cost.

TABLE 3-2

COST SUMMARY FOR E-SOX

	Capital Cost		First Year Operating and Maintenance Cost	
Case No.	$1000	$/kW	$1000/yr	Mills/kWh
1	19,100	38	6,890	2.42
2	23,700	47	7,090	2.49
3	22,700	45	7,040	2.47
4	19,400	39	6,990	2.45
5	19,100	38	7,580	2.66
6	15,900	32	6,170	2.16

As a means to compare overall costs of the systems, Table 3-3 presents total first-year costs on an annualized basis, as well as costs per ton of SO_2 removed. The costs per ton of SO_2 removed indicate that E-SOX technology, if it can be successfully commercialized, should compete very favorably with other retrofit SO_2 removal technologies.

TABLE 3-3

FIRST-YEAR ANNUALIZED COSTS OF E-SOX ($1000/YR)

	Case No. 1	2	3	4	5	6
Annualized Capital Cost	3,440	4,260	4,090	3,500	3,440	2,870
First Year O&M Cost	6,890	7,090	7,040	6,990	7,580	6,170
Total First Year Annualized Cost	10,330	11,350	11,130	10,490	11,020	9,040
$/ton SO_2 Removed	348	382	375	353	371	305

In summary, the following conclusions can be drawn:

- The mechanical system design for the most part utilizes commercially available equipment. The only items that pose developmental problems are the two-fluid nozzle spray system, the ESP precharger, and the ESP large-diameter electrodes.

- From an operating point of view, the greatest concern is adequate spray drying in the gutted first field of the ESP to minimize tenacious deposits in the subsequent ESP fields. (Note: this analysis was made with the assumption that spraying of solid would occur in the gutted first ESP field, not in a separate spray chamber.)

- ESP performance on this type of particulate needs to be verified. In particular, the mass loadings and size distribution of the particulate at the end of the spray section, the ESP electrical properties (secondary voltages and currents), and gas distribution device requirements need to be established. (Authors' note: See the previous note given at the end of Table 3.1.)

- The capability of a vacuum-type fly-ash handling system to continuously remove hopper material needs to be

demonstrated. Additional equipment requirements (for example a delumper to prevent oversize material) need to be defined.

- Retrofit capital costs will be very site specific, particularly if conventional ESP modifications (taller plates or an outlet field) are required.

- The largest single component affecting the operating cost is the reagent consumption. Therefore, process stoichiometry is critical to cost. Also, pebble lime shows a distinct economic advantage over lime hydrate.

- Future research efforts should be concentrated on optimizing the process parameters — in particular, slurry droplet size, Ca/S ratio, approach temperature, and residence time requirements.

- Because of the performance advantages indicated by the precharger and large diameter electrodes, these technologies should be further demonstrated at an appropriate equipment scale.

(Authors' note: The conclusion about the usefulness of the precharger now seems difficult to support in view of the earlier statement, on page 8, to the effect that the precharger offers little performance advantage for a low-resistivity dust, which is likely always to be encountered in the E-SOX process. On the other hand, a reviewer of this report has suggested that a precharger might give relief from the corona-quenching effects of space charge on particle charging; whether this suggestion can be firmly supported by experimental data is questionable. As far as the large diameter electrodes are concerned, their utility may be limited with the low resistivity of E-SOX dust. Increasing the diameter of the discharge electrodes increases the electric field at the surfaces and may exacerbate the reentrainment of low-resistivity particles.)

SECTION 4

MEASUREMENT AND MODELING OF THE PERFORMANCE OF A PRECHARGER

Introduction

Conceptual designs for a retrofit application of E-SOX technology have often included the installation of a precharger in front of the rebuilt sections of ESP electrodes. The purpose of the precharger is to achieve very high levels of charge on dust particles entrained in the gas stream in a very short distance along the direction of gas flow. One effective type of precharger is the cold-pipe configuration developed by Denver Research Institute. Prechargers of this type are installed in the EPA pilot precipitator in the H300 laboratory at the Air and Energy Engineering Laboratory (AEERL), Research Triangle Park, NC. An alternative purpose of using a precharger might be to alleviate the quenching effect of particle-related space charge on the charging process; this role of a precharger, however, is speculative and might not be borne out in practice.

The only available information on the particle-charging effectiveness of the cold-pipe precharger consisted of a charge/mass (Q/M) measurement performed several years ago with an impactor having an electrically isolated stage. This data point was used for estimates of particle-charging effectiveness in the technical and economic evaluation of E-SOX presented in Section 3 of this report. The subsequent measurements described in this section constitute the first detailed analyses of precharger performance.

One of the objectives of this work was to establish a capability for mathematical modeling of the precharger performance, for future use in design and evaluation of ESP retrofit configurations for E-SOX technology. As will be shown in this section, the configuration of the cold-pipe precharger can be approximated by a wire-plate geometry, which permits application of Southern Research Institute's mathematical model of electrostatic precipitation to the calculation of particle charge (4). Another applicable model has recently been published (5,6). It is based on cylindrical boundaries at the counter electrodes and therefore represents a more direct application of the boundary conditions. The results in Reference 4, however, show very close agreement between the two methods, which lends support to the computed results in this report. Nevertheless, it should be noted that the newer model has the obvious advantage of permitting direct input of dimensions describing the parallel wire-cylinder arrangement of electrodes in the precharger. It is expected that this new model will be very useful in future studies.

Experimental Facility

The measurements of precharger performance were made at AEERL in the H300 laboratory. The only portion of the precipitator that was energized was a single precharger consisting of one discharge wire suspended vertically between two water pipes (2.375 in. in diameter). A top view of the

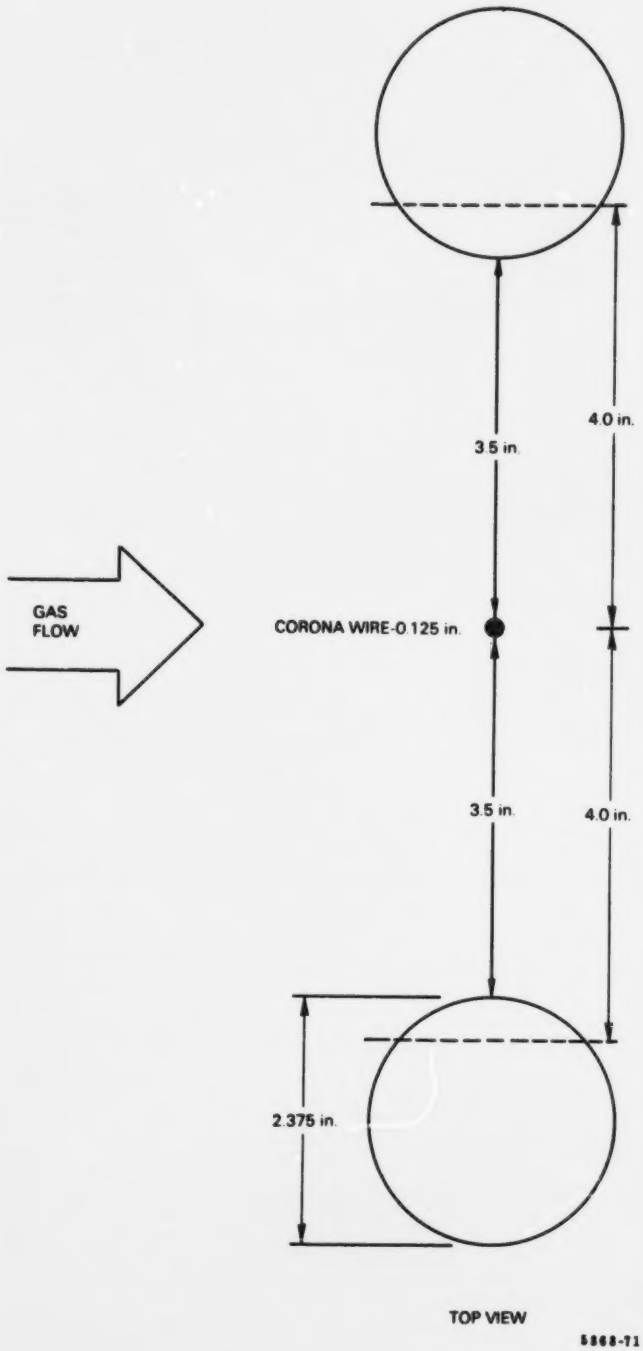

Figure 4-1. Top view of the cold-pipe precharger geometry. The dashed lines show a wire-plate geometry that yields equivalent particle charge values for the same electrical operating point.

particle size distribution and the requirements for isokinetic sampling geometry is given in Figure 4-1. Redispersed fly ash was injected into the ESP inlet air stream. At 300 °F, the average air velocity was about 6 ft/s. Tap water was sprayed into the air stream through a single nozzle in the dry scrubber chamber. At the position of the precharger, the air stream was cooled to about 200 °F, with about 4%-by-volume moisture. Tap water was circulated through the two precharger pipes. Charged fly ash particles were sampled about 6 ft downstream of the precharger. The were irrelevant in this experiment. Only individual particles, one at a time, were tested for size and charge. The tests were performed with Millikan cells (7).

Experimental Results

The charges and sizes of individual fly ash particles were measured in two different Millikan cells set up side-by-side and operated for three days. Five different persons participated in the data acquisition. The data sets from the two different setups were analyzed separately to check for any systematic differences in the experimental results. There were no differences in the two data sets for a given precharger electrical operating point; thus, the two data sets were combined to give better statistical reliability. There resulted 300 to 400 data points for three different precharger electrical operating points:

Voltage, kV	Current, mA	Current density, nA/cm^2
35	0.08	41
40	0.18	91
45	0.21	108

Three sets of particle charge data for the three electrical points are shown in Figures 4-2, 4-3, and 4-4 as individual particle charge values plotted against particle diameter. The statistical data are summarized (for every other particle size band) in Table 4-1. The measured average particle charge values increased only slightly with the increase in precharger energization.

Mathematical Modeling

For each of the three precharger electrical operating points, theoretical particle charge values were computed from the ESP model for comparison with the Millikan data. Particle charge values were computed for four different hypothetical wire-plate geometries in an effort to find a wire-plate geometry that was approximately equivalent to the cold-pipe precharger in particle charging effectiveness. The four geometries were as follows:

Plate length, in.	Wire-plate spacing, in.
6.0	3.0
6.0	4.0
2.4	3.0
2.4	4.0

TABLE 4-1

SUMMARY OF MILLIKAN CELL MEASUREMENTS OF THE CHARGING OF FLY ASH PARTICLES BY A COLD-PIPE PRECHARGER

5/14/87

Precharger Operating Point: 35 kV, 0.08 mA, 41 nA/cm^2
Millikan Cell Bias: 10 volt

Mean Particle Diameter, μm	Number of Particles	Mean Charge Units	Standard Deviation
0.6	9	47	15
1.0	68	153	62
1.4	52	299	113
1.8	26	569	162
2.2	17	876	350
2.6	11	1233	421

5/12/87

Precharger Operating Point: 40 kV, 0.18 mA, 91 nA/cm^2
Millikan Cell Bias: 10 volt

Mean Particle Diameter, μm	Number of Particles	Mean Charge Units	Standard Deviation
0.6	7	62	29
1.0	54	152	59
1.4	42	335	103
1.8	26	631	205
2.2	9	1005	374
2.6	5	1143	126
3.0	2	1628	297

5/13/87

Precharger Operating Point: 45 kV, 0.21 mA, 108 nA/cm^2
Millikan Cell Bias: 10 volt

Mean Particle Diameter, μm	Number of Particles	Mean Charge Units	Standard Deviation
0.6	10	63	14
1.0	68	176	70
1.4	48	347	127
1.8	29	645	152
2.2	19	967	301
2.6	11	1417	305
3.0	3	1619	46

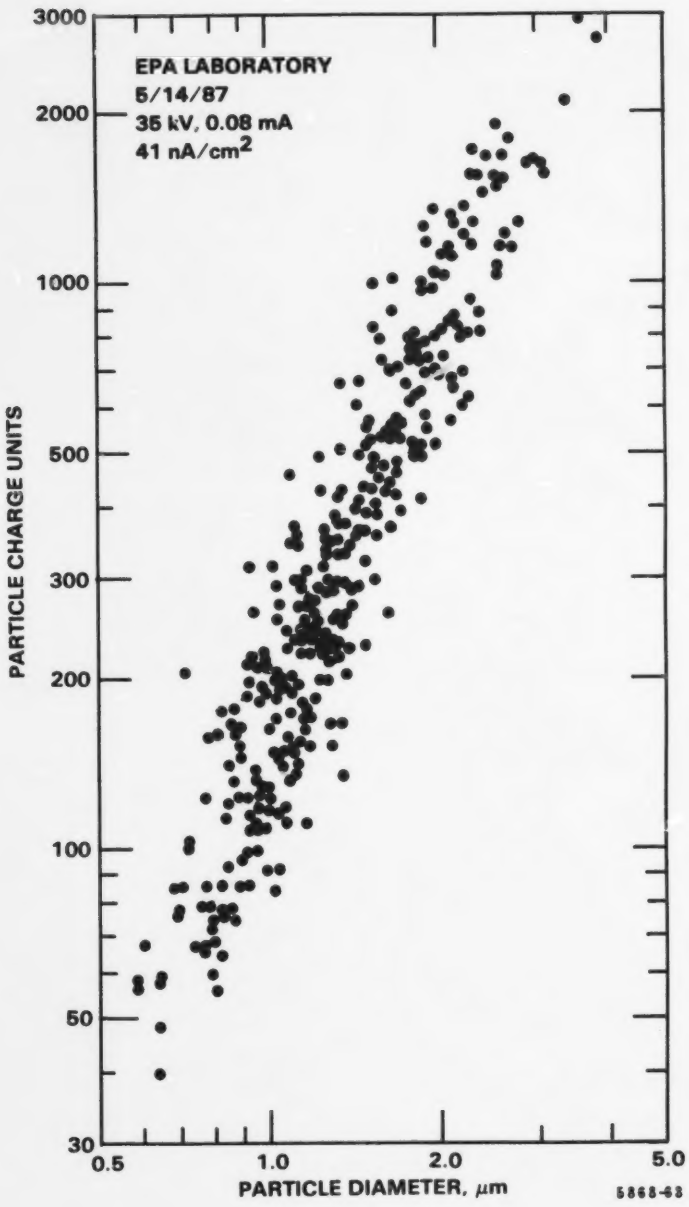

Figure 4-2. Millikan data obtained with the lowest precharger electrical operating point.

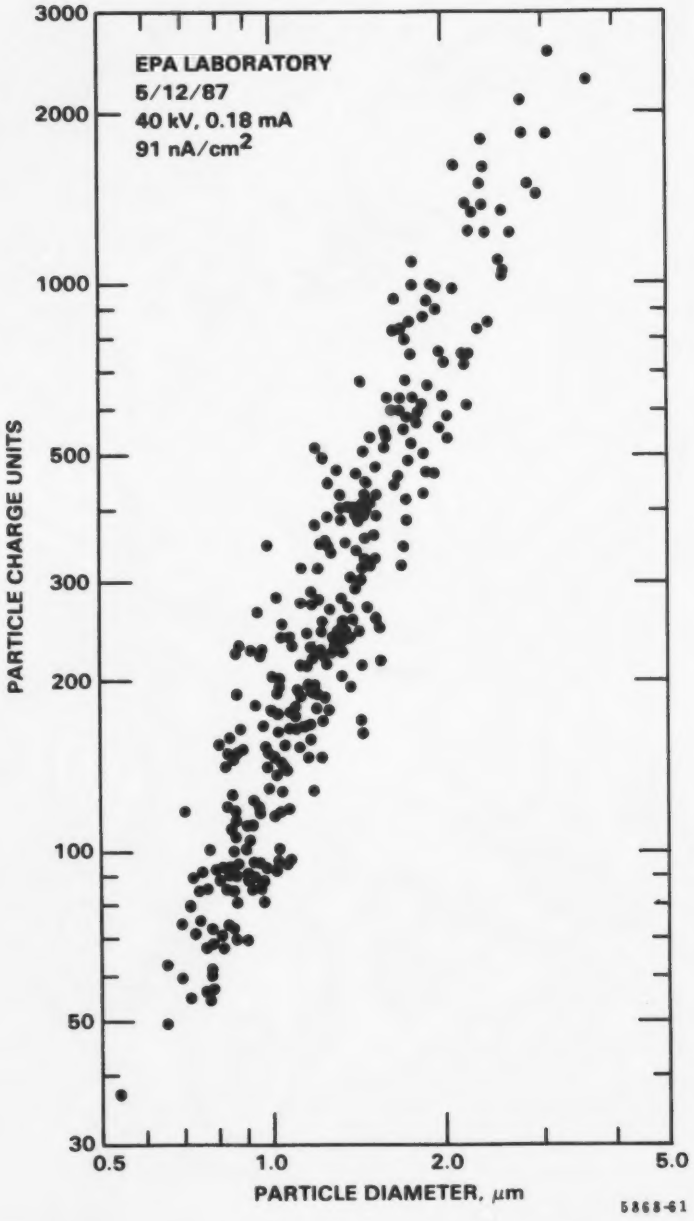

Figure 4-3. Millikan data obtained with the intermediate precharger electrical operating point.

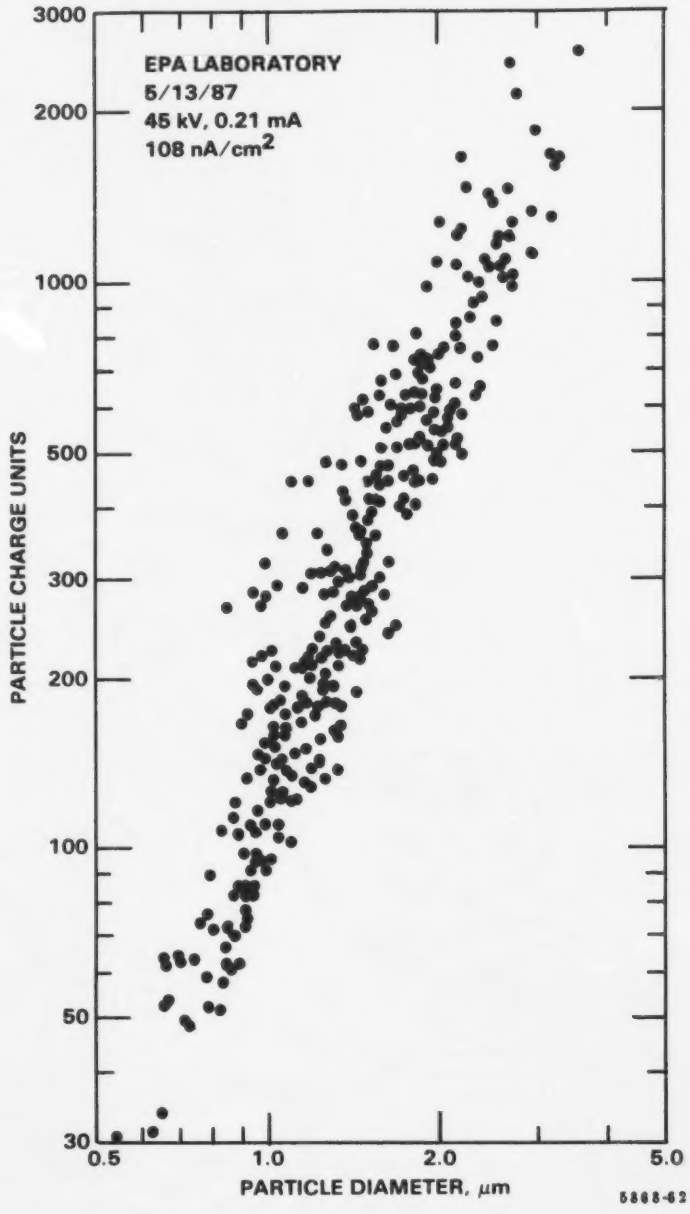

Figure 4-4. Millikan data obtained with the highest precharger electrical operating point.

The computed curves of particle charge values were superimposed on the Millikan data in the preceding figures. The particle charge values computed for the last configuration listed above (plates 2.4 in. long and 8.0 in. apart) were in best agreement with the three sets of experimental data; thus, this configuration was judged to be the closest rectangular simulation of the actual precharger geometry.

The final conclusion, thus, is that the cold-pipe precharger can be approximately represented by an equivalent wire-plate geometry (as illustrated in Figure 4-1) for the purpose of ESP performance evaluations.

Precharger versus Conventional ESP

The mathematical modeling was extended to obtain a comparison between the cold-pipe precharger and the inlet field of a conventional ESP in regard to the effectiveness of particle charging. The comparison is given for ordinary fly ash from pulverized coal combustion as a function of ash resistivity.

The ESP model (4) was used to compute fly ash particle charging in a conventional ESP as a function of treatment time, particle diameter, operating voltage, and average plate current density. The correlation between the ESP electrical operating point (voltage and current density) and the fly ash resistivity was derived from an ESP data base (8). This correlation, which is available as a user option in the ESP model, represents the average trend among the precipitators in the data base. The gas velocity was chosen to be 5.0 ft/s in order to give a simple conversion between time and distance. (The average air velocity varied approximately from 5.0 to 6.5 ft/s as the air stream passed through the precharger in the H300 laboratory.) The comparison between the precharger and the required length of a conventional gas passage was made for different values of fly ash resistivity in the range of 1×10^{10} to 1×10^{13} ohm-cm and for ash particle diameters of 0.6 and 1.8 μm.

The results of calculations of charging in the conventional ESP, given in Figure 4-5, indicate that the precharger offers little advantage in a situation of low dust resistivity and high useful electrical power consumption in a conventional ESP. The particle charge levels achieved by the precharger (in about 0.04 s) would be achieved anyway within a short distance along the gas passage (in about 0.4 s). This conclusion is consistent with the performance estimates of ESP retrofit configurations in the E-SOX technical and economic evaluations presented in Section 3. In that analysis, the ash-sorbent resistivity was assumed to be controlled at about 1×10^{10} ohm-cm by the combination of low gas temperature and high moisture resulting from the evaporation of lime slurry droplets. In Case 2 of that analysis, the ESP performance improvement achieved by installing a precharger and rebuilding the electrodes could alternately be achieved by adding 3 ft of electrified gas passage, probably within an existing casing.

The results in Figure 4-5 show, on the other hand, that if the resistivity should increase from 1×10^{10} to 1×10^{12} ohm-cm (perhaps not a

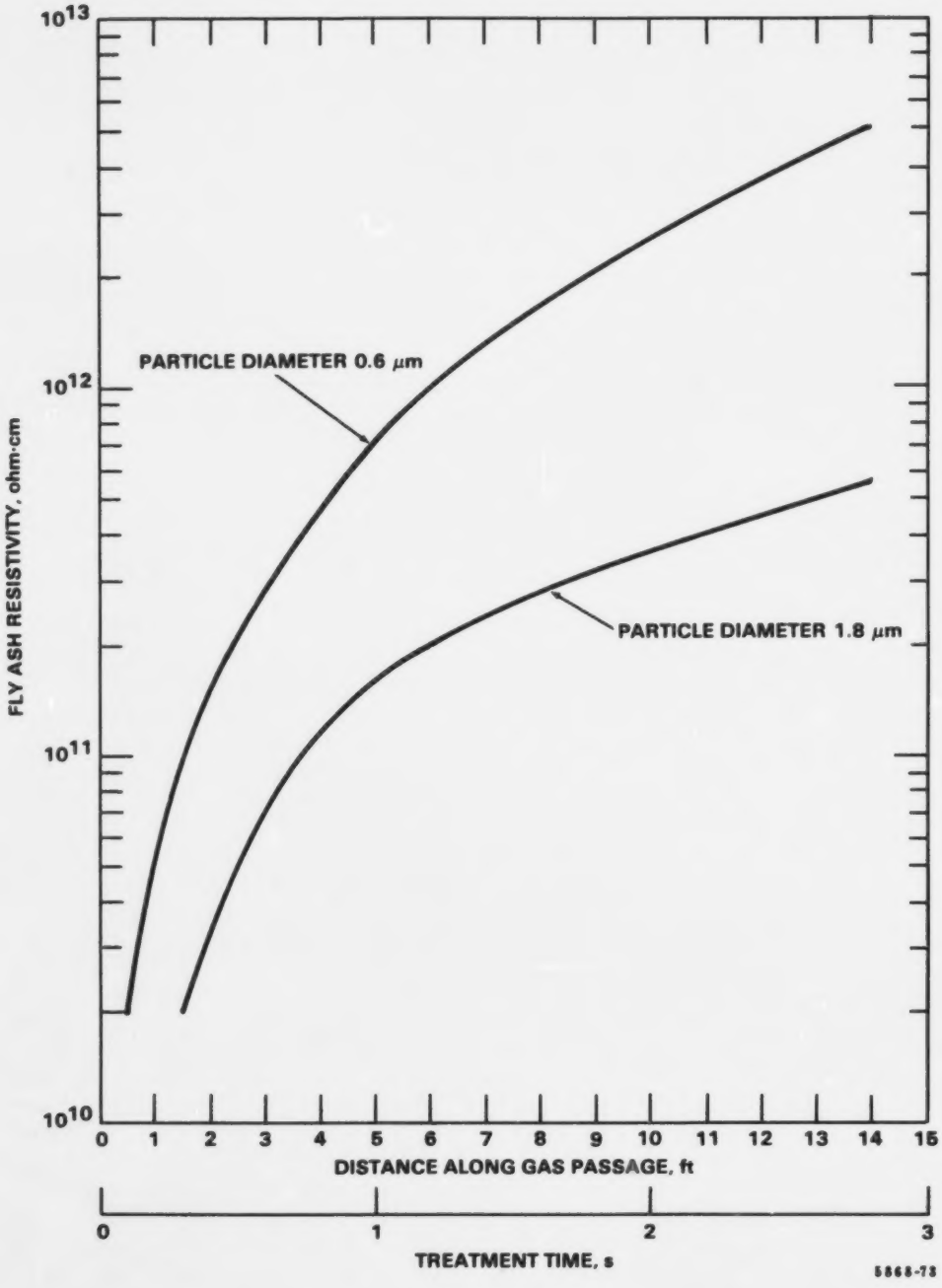

Figure 4-5. Estimates of the distance and treatment time along a convention ESP gas passage that are required to obtain the fly ash particle charge values achieved by the cold-pipe precharger.

realistic value, which would be more nearly representative of unconditioned ash-sorbent mixtures in a dry environment), the cold-pipe precharger would offer a dramatic advantage in particle charging effectiveness. With increasing values of resistivity, the useful values of operating voltage and current density (that is, the values obtained below the onset of severe back corona) become severely limited in a conventional ESP. One result is that it takes longer and longer to charge particles. The cold-pipe precharger was developed by Denver Research Institute specifically for the purpose of charging dust particles in situations of high electrical resistivity of precipitated dust layers.

In addition to showing that the cold-pipe precharger has a distinct advantage for charging particles with high resistivities, Figure 4-5 shows that the advantage is even more dramatic for larger particles. This trend with particle diameter can be understood in terms of particle charging predominantly by molecular ions driven by the applied electric field, as opposed to charging by ions in thermal diffusion. The charging rate is directly proportional to the interelectrode electric field. Some comparative numerical values can be obtained from the ESP model simulations of both the precharger and the conventional ESP. With the equivalent wire-plate geometry of the precharger (Figure 4-1) and an applied voltage of 45 kV, regardless of the dust resistivity, the average interelectrode electric field is 4.4 kV/cm. (In the actual precharger, the local electric fields near the curved surface of the pipes are even higher.) In the conventional ESP, the average interelectrode electric field is 3.9 kV/cm with fly ash resistivity of 1×10^{10} ohm-cm but decreases to 3.4 kV/cm as the resistivity rises to 1×10^{11} ohm-cm and then decreases to 3.0 kV/cm as the resistivity rises to 1×10^{12} ohm-cm. Furthermore, in the conventional ESP, the electric field values are smaller near the flat surface of the collecting plate.

Reentrainment Emissions

The foregoing comparisons of particle charging effectiveness have been made in relation to the inlet field of a conventional ESP. However, a consideration of reentrainment emissions at the ESP outlet is at least equally important. Reentrained dust tends to be agglomerated into larger particles that are charged mainly by the applied electric field. The trend of the curve for 1.8 μm particles in Figure 4-5 indicates that a conventional ESP outlet field cannot adequately recharge large particles that have been reentrained from precipitated dust layers of very high electrical resistivity.

These data illustrate the opportunity that exists to improve the performance of ESPs substantially by using novel outlet field configurations to suppress reentrainment emissions. A cold-pipe precharger could be used in front of a wet collector stage. The entire after-collector could be contained in a distance of about 4 ft. Because of industry resistance to novel ESP electrode configurations, however, this concept was deleted from consideration in the E-SOX technical and economic evaluations presented in Section 3.

SECTION 5

REVISION OF THE MATHEMATICAL MODEL OF ELECTROSTATIC PRECIPITATION

Several versions of a model of electrostatic precipitation have been developed by Southern Research under EPA auspices. The latest version previously described was completed in 1984 (4). Work to develop an even further version was pursued as part of the present investigation; the work was brought to a conclusion under another Cooperative Agreement (CR-812811) and described in detail in a topical report that recently was submitted to EPA in draft form under that other cooperative agreement. The motivation for making the latest revision was to increase the accuracy of the model in treating certain problems that may be encountered in unusual circumstances, as with E-SOX or LIMB. Another effort brought to conclusion under the other cooperative agreement was the development of a user-friendly data entry routine, which is of help in the use of either the preceding versions or the current version of the ESP model. This development is the subject of still another topical report that was recently submitted to EPA for review.

A self-consistent Deutschian ESP model. The ESP model developed by Southern Research for EPA provides an acceptable simulation of the performance of cold-side utility fly ash ESPs with typical values of inlet mass loading. To increase the accuracy of model predictions in unusual situations, such as high inlet mass loading or abnormally low current density, a revised version of the model was developed. The revised model is unique in that it rigorously calculates the effects of particulate space charge on the interelectrode electric field and on subsequent particle charging.

This report provides operating instructions for the revised model, with examples of the input and output data. A discussion of the theory of the model is also included. Although the revised ESP model was developed on a main-frame computer, it can be run on an IBM PC-compatible microcomputer.

A user-friendly data entry routine for the ESP model. All versions of the Southern Research ESP performance model have very exacting format requirements for the input data sets. Southern Research has now written a program that greatly simplifies the creation and modification of ESP model data files, thereby eliminating one of the major sources of error in the use of the model. This program, which is written for IBM PC-compatible computers, has the following features:

1. The data are displayed in a set of menu-driven data forms. Each item is entered by typing the correct number in the space provided.

2. Each data item is identified by description as well as by variable name.

3. The program reads and writes data files in the standard ESP model data format. The data files written by the program may be used by any Southern Research ESP model.

4. When the program begins, a set of ESP data is displayed as a guide in selecting suitable data values. Any ESP data set may be used for the startup data.

This report serves as a user's manual for the data entry program. It describes each step which the user must follow in order to use the model successfully. A complete description of the ESP model input data is included as an appendix. Forms for organizing data before using the data entry program are also included.

SECTION 6

STUDIES OF THE E-SOX PROCESS IN A PILOT-SCALE COMBUSTOR

Southern Research Institute operates a pilot-scale combustor on its premises in Birmingham. The combustor has a normal capacity rating of 1×10^6 Btu/h with either coal or natural gas as the fuel. The equipment associated with the combustor includes a spray chamber in the line that carries combustion gases to the exhaust; thus, the apparatus was found useful for pilot-scale studies of the E-SOX process, which were carried out on a limited scale.

One purpose of operating the combustor in the E-SOX mode was to generate samples of solids that simulate the mixture of fly ash and sorbent that is produced by the E-SOX process. These solids were characterized in various ways: chemical analysis, thermogravimetric analysis, scanning electron microscopy, Bahco particle sizing, surface area measurement, and electrical resistivity measurement. The primary emphasis was on resistivity; the results of measurements of this property are described in Section 7. The samples were generated in the combustor by 1) burning a Pittsburgh No. 8 coal that produced about 0.22 mole of SO_2 and 0.064 mole of water vapor per mole of dry gas and 2) injecting a spray of commercial hydrated lime that gave a Ca/S ratio of 1.6 and raised the humidity level to 0.13 mole of water vapor per mole of dry gas. The time allowed for reaction between the SO_2 and the $Ca(OH)_2$ was approximately 10 s. The samples were collected in a Fisher-Klosterman EX-S2 classifier through a probe inserted at the outlet of the humidification chamber.

Another purpose of studies with the pilot-scale combustor was to compare SO_2 removals with lime slurries prepared in either of two ways: 1) mixing commercial hydrated lime with water or 2) slaking commercial quicklime in the water to be used for injecting the resulting slaked lime. As stated above, samples of E-SOX solids were initially generated with a slurry prepared from a commercial hydrate. On the other hand, the normal practice with E-SOX would be to prepare the slurry from quicklime. For normal practice, quicklime is the less expensive raw material. Of more concern, quicklime may give a more reactive product and thus should be used to prepare representative samples of E-SOX solids.

The effectiveness of SO_2 removal with each type of slurry was determined on the basis of measurements of changes of the SO_2 concentration in the gas phase and on the basis of increases in the sulfite content of the waste solids. The data were more consistent for the slurry made from hydrated lime but still indicated that the extent of SO_2 removal was slightly higher with quicklime. The removals of SO_2 at an approach to adiabatic saturation of 50 °F were as follows:

	Lime utilization	
Data source	Hydrated lime	Quicklime
Gas-phase data	34%	41%
Solids analysis	37%	40%

Although the slurry prepared with quicklime seemed marginally superior, there did not seem to be any reason for concern about the representativeness of solids prepared with hydrated lime or about the resistivity data obtained with the solids derived from hydrated lime.

SECTION 7

MEASUREMENT AND PREDICTION OF THE ELECTRICAL RESISTIVITY OF SOLIDS PRODUCED BY PROCESSES FOR SO_2 CONTROL

These topics are of major importance when the solids produced by such processes as E-SOX or LIMB are to be removed from the gas stream in an ESP. Both topics received major attention during the present investigation; the results from this effort are discussed in detail in a topical report that was submitted to EPA for review in December 1990. The contents of that report are described in summary fashion in the following paragraphs.

Revised method of measurement. The presence of large amounts of partially spent sorbent along with fly ash in the waste solids from the E-SOX or LIMB process makes it necessary to alter the procedure that is appropriate when fly ash is present alone. The IEEE Standard 548-1984 procedure for measuring resistivity, when applied to ash-sorbent mixtures, yields inconsistent and unrepeatable data and, in particular, major discrepancies between data recorded with ascending or descending temperatures. These difficulties are traceable to major changes in the nature of the solid that is caused by heating to 450 °C, as specified by the Standard. $Ca(OH)_2$, which may be present in LIMB solids and will generally be present in E-SOX solids, is subject to dehydration to CaO around 300 °C. Large changes in surface area, as illustrated in Figure 7-1, result from the dehydration process; not surprisingly, large changes in resistivity accompany these variations in surface area.

The nature of a solid containing $Ca(OH)_2$ can only be maintained in the process state if the solid is not heated above 250 °C during the resistivity measurement. Even with this provision, however, resistivity measured with the ascending temperature technique does not show good repeatability; the first measurement gives a result that is lower than the results obtained on subsequent measurements with identical conditions. In contrast, resistivity measured with the descending temperature technique shows excellent repeatability and consistency. Therefore, the resistivity of ash-sorbent mixtures should always be measured at descending temperatures. As mentioned below, however, the validity of laboratory measurements on the resistivity of ash-sorbent mixtures remains in doubt, whether the data from the laboratory are repeatable and self-consistent or not.

Prediction of resistivity. Partially spent sorbent will, in general, contain a variety of calcium compounds in addition to $Ca(OH)_2$, including the sulfite, the sulfate, the carbonate, and the oxide. These compounds have widely differing resistivities, as depicted in Figure 7-2. (No data for the oxide, which has not been measured, are included in this figure because of the expected transformation of the oxide to the hydroxide in the presence of the water vapor that is used in the measurement procedure). The data for E-SOX and LIMB samples in Figures 7-3 and 7-4 make it appear that the resistivities of these solids may be determined primarily by one of more of the individual calcium compounds.

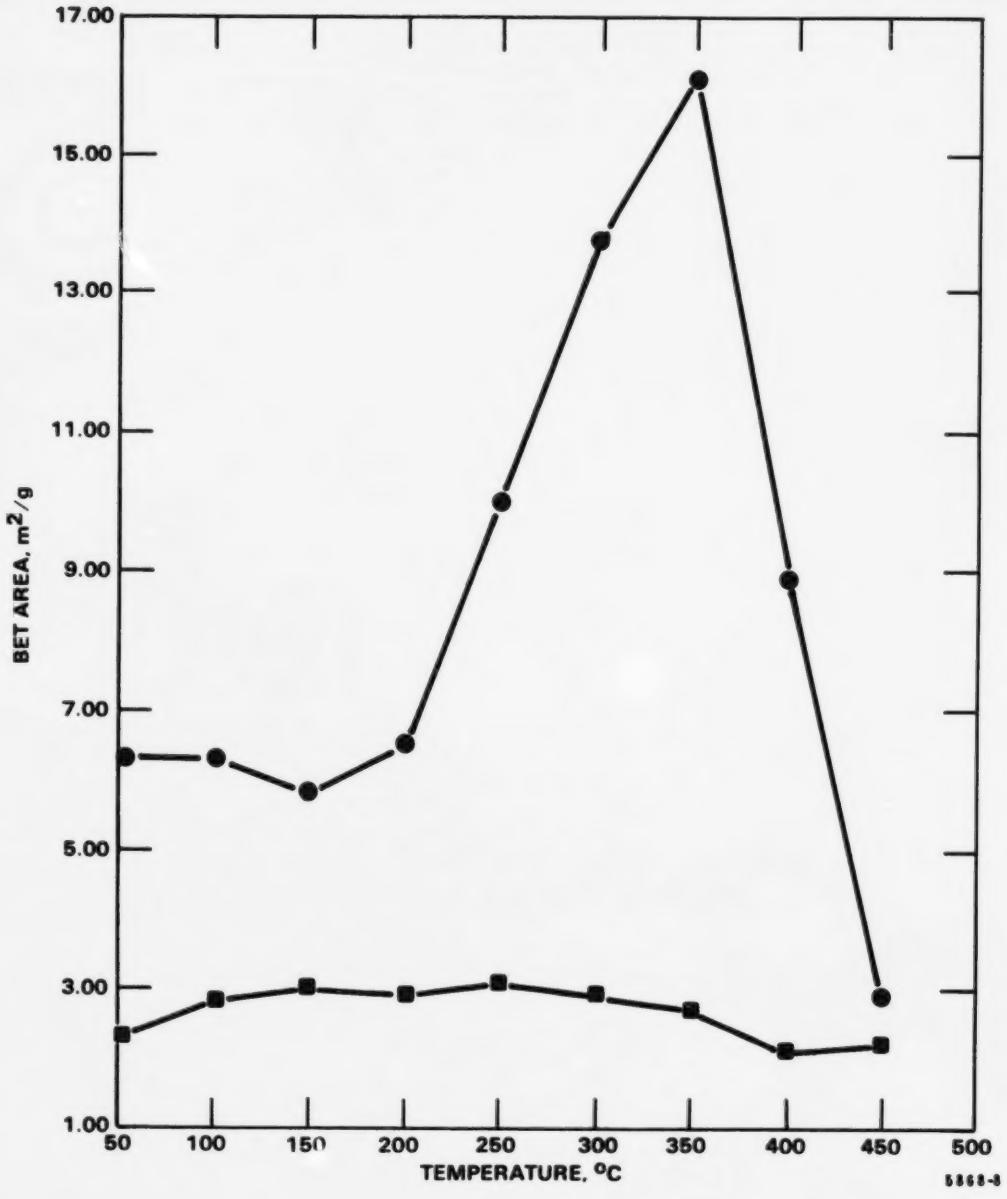

Figure 7-1. BET area as a function of annealing temperature in an atmosphere containing 10.4% humidity by volume. Circles are for the E-SOX sample; squares are for a LIMB sample.

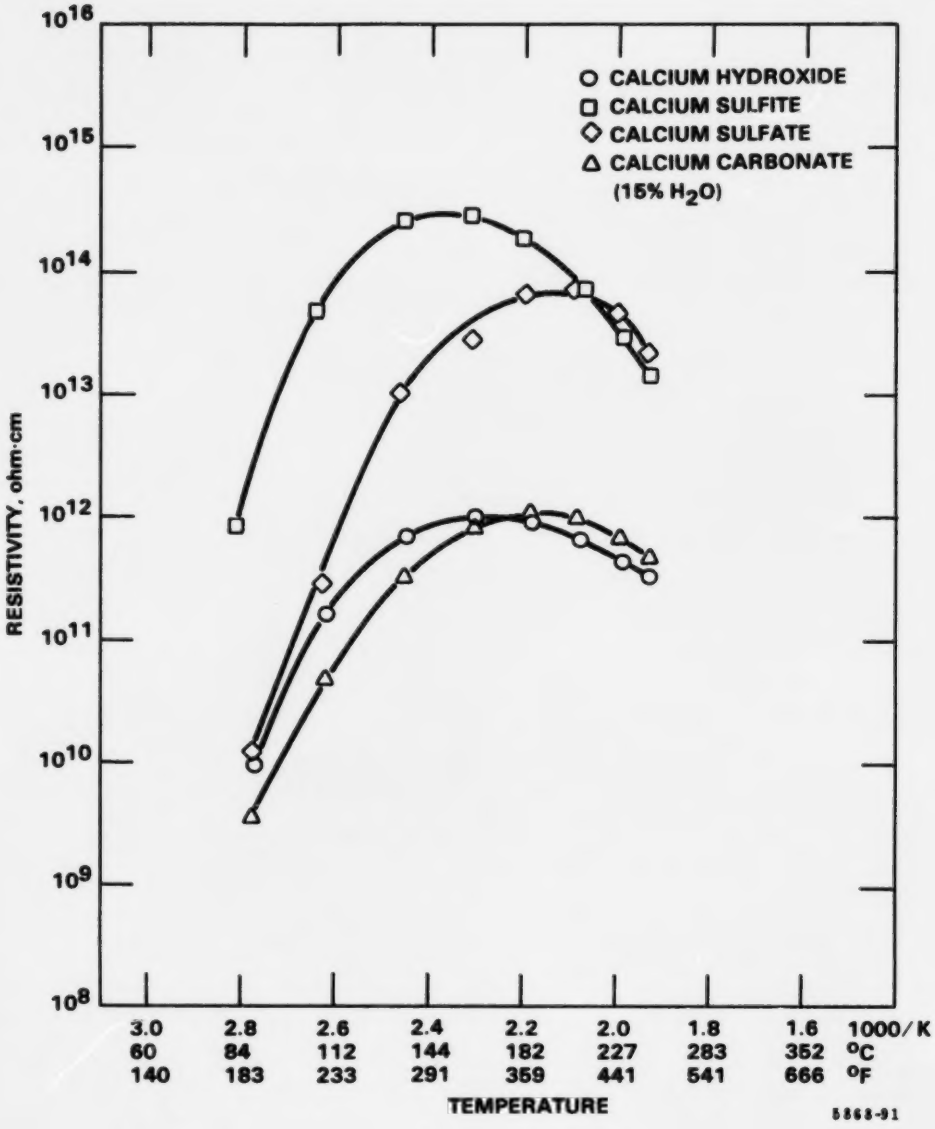

Figure 7-2. Resistivities of calcium compounds expected to be present in ash/sorbent mixtures.

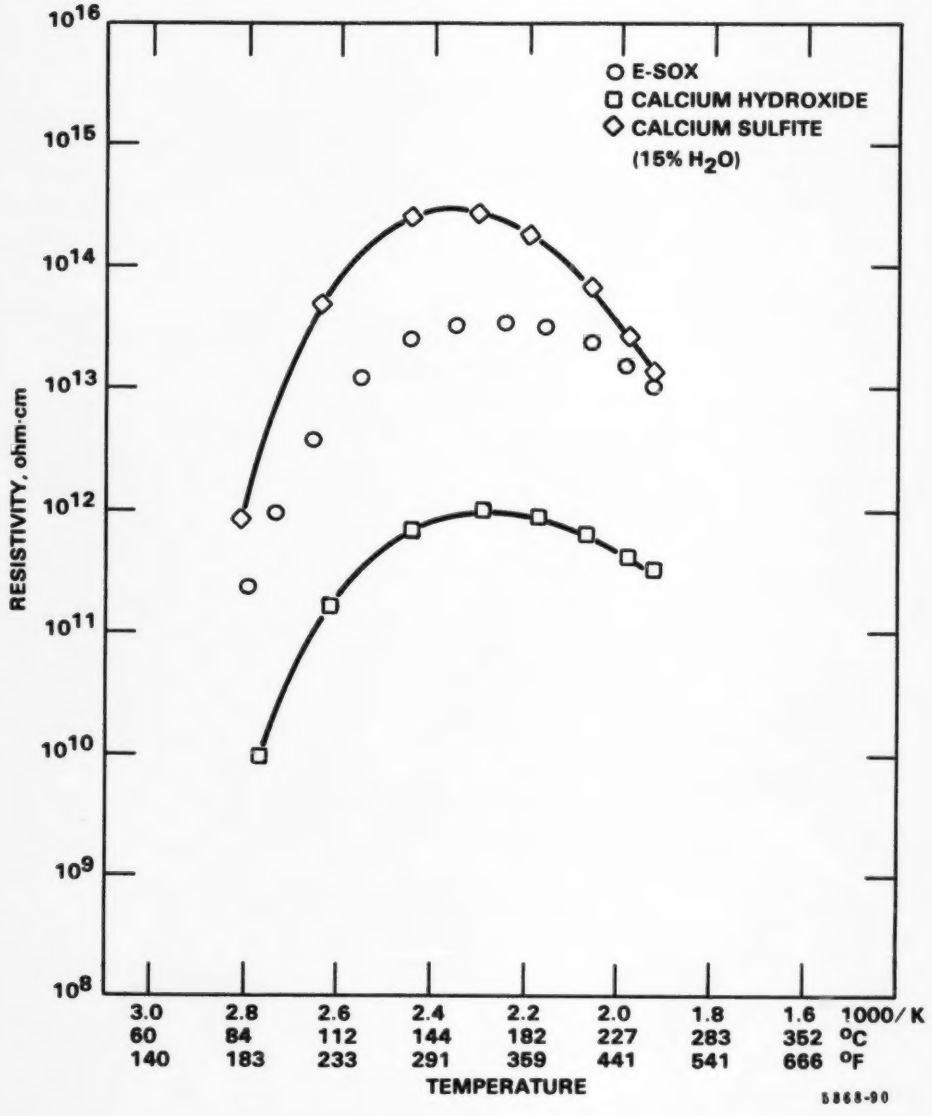

Figure 7-3. Comparison of the resistivities of an E-SOX sample, calcium hydroxide, and calcium sulfite.

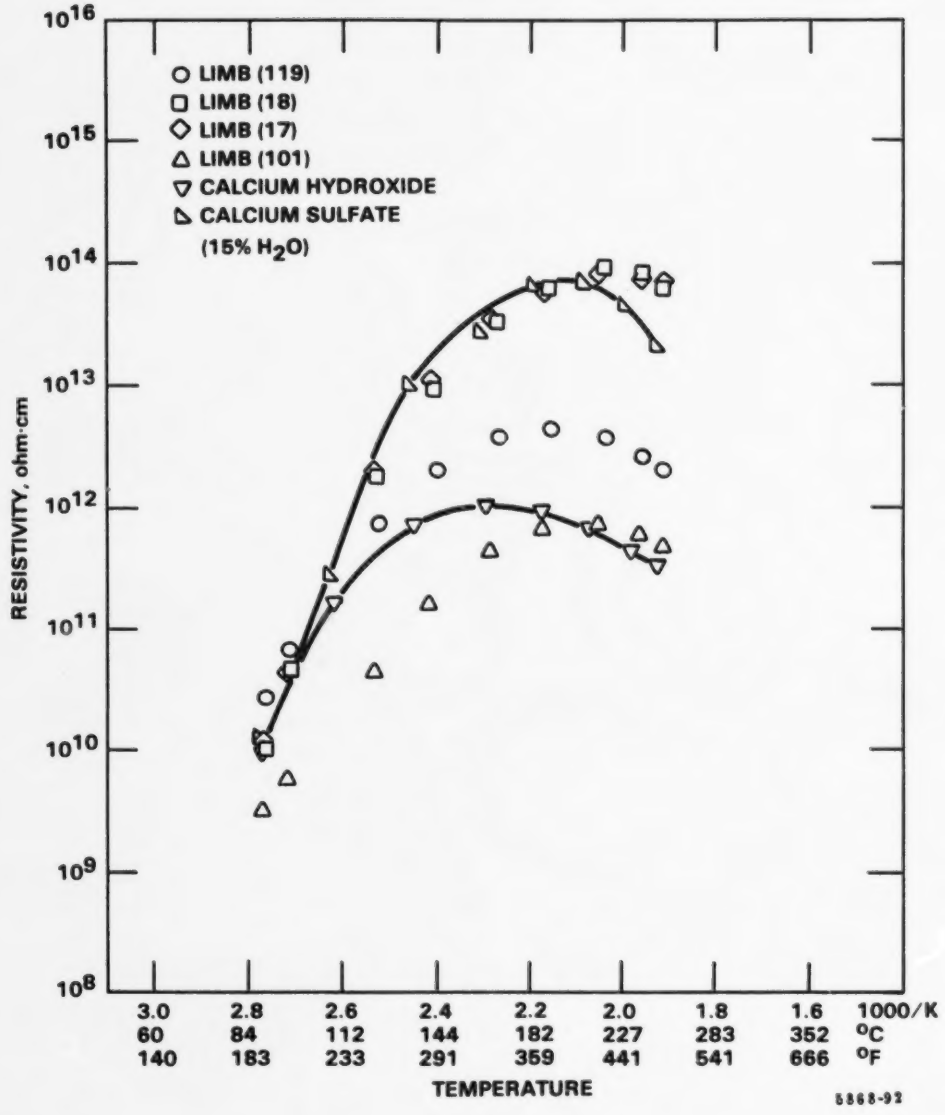

Figure 7-4. Comparison of the resistivities of 4 LIMB samples (17 and 18 with hydrated lime injection, 101 and 119 with limestone injection), calcium hydroxide, and calcium sulfate.

The method developed by Bickelhaupt (9) for predicting the resistivity of fly ashes is not satisfactory for predicting the resistivity of ash-sorbent mixtures. This is hardly surprising, because the range of ash compositions used in developing the predictive method does not extend to the high concentrations of calcium that is present in ash-sorbent mixtures. This difficulty seemed possible to overcome with the new data of ash-sorbent mixtures. For example, multiple regression analyses of the resistivity data showed very strong correlations between the resistivities of the ash-sorbent mixtures and the resistivities of the individual calcium compounds. Based on these correlations, considerable work was done to develop a predictive method that would be satisfactory for ash-sorbent mixtures; nevertheless, this effort was unfortunately not successful. The lack of success was apparently due to a considerable degree to the inability to describe the compositions of the mixtures as fully as required.

Further research needs. The need for an adequate method for predicting the resistivity of ash-sorbent mixtures continues at the present time. The need for more reliability in the experimental measurement of resistivity, whether measurement is done with the material in the field or in the laboratory, must also be recognized as an issue of great importance. Recent comparisons of field and laboratory data have shown that the results of measurements in the field and the laboratory often differ decisively, for reasons that have not been explained (10,11).

SECTION 8

FIELD DEMONSTRATION OF THE E-SOX PROCESS

Only the initial phase of this demonstration was supported by the cooperative agreement discussed in this report; the principal support came from Cooperative Agreement CR-814915. A brief discussion of the demonstration, however, is given in the following paragraphs.

This demonstration is being performed at the Burger power station of the Ohio Edison Company at the 5-MW scale. A key component of the facility being employed is the pilot-scale ESP, which was moved to the Burger site from its former location at the Valmont station of the Public Service Company of Colorado. This ESP has four electrified fields; it has cold-pipe charging electrodes in each field, but they were not employed in the testing performed to date. The ESP is preceded by a spray chamber, where a slurry of slaked lime is injected. At the inlet to the first field of the ESP there is a droplet-impingement device, which intercepts and removes large slurry droplets and dry residues of droplets. The remaining smaller particles are then subject to collection in the ESP. The apparatus and status of testing as of May 1990 have been described by Redinger of Babcock & Wilcox (12).

Testing of the ESP performance was conducted by Southern Research. The principal finding was that the efficiency of solids collection deteriorated markedly when operation with E-SOX began. The explanation for the deterioration is that the dried sorbent particles had very low cohesiveness and as a consequence were extensively reentrained after precipitation. The results of the ESP testing have been presented by Marchant et al. (13).

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13. Marchant, G. H., Jr., J. P. Gooch, M. G. Faulkner, and L. S. Hovis. Effects of E-SOX Technology on ESP Performance. Presented at the Eighth EPA/EPRI Symposium on the Transfer and Utilization of Particulate Control Technology, San Diego, CA. March 1990.

APPENDIX A

DATA BASE OF ELECTRIC UTILITY PLANTS FOR USE WITH THE E-SOX PROGRAM
(See Section 2)

100 < SCA < 125, SUM OF MW = 1564

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
525	E. W. Brown 2	1	115	2.09	156	KY	1975
968	Paradise 1	2	117	4.20	704	KY	1967
969	Paradise 2	3	117	4.20	704	KY	1967

125 < SCA < 150, SUM OF MW = 4731

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
278	Allen 1	1	150	0.91	165	VA	
279	Allen 2	2	150	0.91	165	VA	
17	Gorgas Two 10	3	145	1.43	700	AL	1972
162	Avon Lake 8	4	140	2.47	233	OH	1959
454	Petersburg 2	5	127	2.54	471	IN	1974
494	Burlington 1	6	135	2.60	212	IL	1981
382	Crist 6	7	137	2.60	320	AL, OH, KY	1970
118	Grand Tower 3	8	133	2.80	86	IL	1969
119	Grand Tower 4	9	143	2.80	114	IL	1970
649	Bailly 7	10	128	3.30	194	IN, IL	1962
52	New Madrid 1	11	136	3.30	600	IL	1972
53	New Madrid 2	12	136	3.30	600	IL	1977
155	Ashtabula 5	13	140	3.90	256	OH, PA, KY	1958
705	Muskingum River 5	14	134	4.37	615	OH	1980

150 < SCA < 175, SUM OF MW = 7429

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
546	Erickson 1	1	170	0.77	165	KY	1973
300	Marshall 1	2	174	1.11	350	KY, VA	
351	Hammond 2	3	165	1.70	100	KY, TN, IL	1969
352	Hammond 3	4	165	1.70	100	KY, TN, IL	1969
887	Jefferies 3	5	157	1.86	173	KY	1979
888	Jefferies 4	6	157	1.86	173	KY	1979
527	Ghent 1	7	173	1.86	511	KY	1973
120	Hutsonville 3	8	160	2.10	75	IL	1971
121	Hutsonville 4	9	160	2.10	75	IL	1971
92	Cardinal 1	10	161	2.10	615	WV	1967
93	Cardinal 2	11	161	2.10	615	WV	1967

150 < SCA < 175, SUM OF MW = 7429

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
827	Wabash River 1	12	156	2.20	113	IN	1971
828	Wabash River 2	13	156	2.20	113	IN	1970
829	Wabash River 3	14	156	2.20	113	IN	1970
830	Wabash River 4	15	156	2.20	113	IN	1970
831	Wabash River 5	16	156	2.20	125	IN	1969
832	Wabash River 6	17	156	2.20	387	IN	1967
934	Colbert 1	18	175	2.30	200	OH	
935	Colbert 2	19	175	2.30	200	OH	
936	Colbert 3	20	175	2.30	223	OH	
937	Colbert 4	21	175	2.30	223	OH	
589	Jack Watson 5	22	173	2.58	578	IL, AL	1973
383	Crist 7	23	158	2.60	500	AL, OH, KY	1973
974	Watts Bar 1	24	161	2.60	60	KY, IN, TN	1969
975	Watts Bar 2	25	161	2.60	60	KY, IN, TN	1969
976	Watts Bar 3	26	161	2.60	60	KY, IN, TN	1969
977	Watts Bar 4	27	161	2.60	60	KY, IN, TN	1969
124	Meredosia 3	28	163	2.80	239	IL	1972
679	Gorge 6	29	151	2.92	44	OH	1979
680	Gorge 7	30	151	2.92	44	OH	1979
823	R. H. Gallagher 1	31	168	3.00	150	IN, KY	1969
824	R. H. Gallagher 2	32	168	3.00	150	IN, KY	1969
825	R. H. Gallagher 3	33	168	3.00	150	IN, KY	1968
826	R. H. Gallagher 4	34	168	3.00	150	IN, KY	1968
650	Bailly 8	35	173	3.30	422	IN, IL	1968

175 < SCA < 200, SUM OF MW = 11,915

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
1005	Bay Shore 3	1	191	0.80	140	WV, KY	
1006	Bay Shore 4	2	194	0.80	218	WV, KY	
169	Lake Shore 1	3	197	0.81	256		1962
214	J. C. Weadock 7	4	198	0.98	156	OH, WV, VA	1971
215	J. C. Weadock 8	5	198	0.98	156	OH, WV, VA	1971
885	Grainger 1	6	190	1.53	82		1975
886	Grainger 2	7	190	1.53	82		1975
676	Edgewater (OH) 2	8	196	1.80	63	OH	1978
677	Edgewater (OH) 3	9	196	1.80	44		1979
370	Yates 2	10	186	1.90	100	KY	1968
371	Yates 3	11	186	1.90	100	KY	1969
372	Yates 4	12	187	1.90	125	KY	1970
373	Yates 5	13	187	1.90	125	KY	1968

175 < SCA < 200. SUM OF MW = 11,915

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
794	Morgantown 1	14	195	1.90	573	PA, MD	1970
795	Morgantown 2	15	195	1.90	575	PA, MD	1971
524	E. W. Brown 1	16	194	2.09	100	KY	1973
971	T. H. Allen 1	17	200	2.30	330	KY	1972
972	T. H. Allen 2	18	200	2.30	330	KY	1971
973	T. H. Allen 3	19	200	2.30	330	KY	1972
811	Cayuga 1	20	180	2.40	531	IN, KY, IL	1970
812	Cayuga 2	21	180	2.40	531	IN, KY, IL	1972
1010	Labadie 3	22	192	2.44	621	IL	1983
1011	Labadie 4	23	192	2.44	621	IL	1984
1008	Labadie 1	24	199	2.44	621	IL	1984
1009	Labadie 2	25	199	2.44	621	IL	1983
163	Avon Lake 9	26	192	2.47	680	OH	1970
418	Hennepin 2	27	196	2.50	231	IL	1972
1098	Weston 2	28	192	2.67	75		1972
122	Meredosia 1	29	189	2.80	58	IL	1972
123	Meredosia 2	30	189	2.80	58	IL	1972
413	Baldwin 1	31	180	2.91	623	IL	1970
414	Baldwin 2	32	180	2.91	635	IL	1973
689	Toronto 6	33	185	2.99	66	OH	1980
690	Toronto 7	34	185	2.99	66	OH	1980
560	Mill Creek (KY) 3	35	187	3.50	463	KY	1978
821	Nobelsville 1	36	177	3.70	50	IN	1972
117	Coffeen 2	37	188	3.70	617	IL	
683	R. E. Burger 1	38	196	3.86	63	OH	1980
684	R. E. Burger 2	39	196	3.86	63	OH	1980
685	R. E. Burger 3	40	196	3.86	100	OH	1980
686	R. E. Burger 4	41	196	3.86	160	OH	1980
703	Muskingum River 3	42	185	4.37	238	OH	1971
704	Muskingum River 4	43	185	4.37	238	OH	1971

200 < SCA < 225. SUM OF MW = 10,298

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
293	Cliffside 5	1	211	1.02	571	KY, VA	
520	Bag Sandy 1	2	212	1.28	281	KY	1970
675	Riverside (MN) 8	3	203	1.30	239		
756	Homer City 2	4	204	1.60	660		
773	Montour 1	5	204	1.60	805	PA	
350	Hammond 1	6	210	1.70	100	KY, TN, IL	1971
348	Bowen 3	7	212	1.70	880	KY	
349	Bowen 4	8	212	1.70	880	KY	

200 < SCA < 225. SUM OF MW = 10,298

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
369	Yates 1	9	210	1.90	100	KY	1971
763	Shawville 1	10	205	2.04	133		
764	Shawville 2	11	205	2.04	133		
367	Wansley 1	12	214	2.20	865	IL, KY, TN	1976
368	Wansley 2	13	214	2.20	865	IL, KY, TN	1978
748	Conemaugh 1	14	206	2.22	936		1980
749	Conemaugh 2	15	206	2.22	936		1980
417	Hennepin 1	16	223	2.50	75	IL	1974
483	Riverside 5	17	214	2.66	128	IL	
1097	Weston 1	18	217	2.67	60		1972
734	Elmer Smith 2	19	201	2.83	265	KY	
419	Vermillion 1	20	217	2.94	74	IL	1973
558	Mill Creek (KY) 1	21	203	3.50	356	KY	1972
559	Mill Creek (KY) 2	22	203	3.50	356	KY	1974
687	R. E. Burger 5	23	214	3.86	160	OH	1979
701	Muskingum River 1	24	209	4.37	220	OH	1972
702	Muskingum River 2	25	209	4.37	220	OH	1972

225 < SCA < 250. SUM OF MW = 7350

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
462	Lansing 3	1	234	0.50	38		
296	Dan River 3	2	242	0.86	150	KY, WV, VA	
9	Barry 5	3	236	0.92	700	AL, TN	
1043	Chesterfield 6	4	231	1.00	694		1983
788	Red Smith 4	5	238	1.10	75	PA, WV	
148	W. C. Beckjord 1	6	236	1.58	100	KY	1974
149	W. C. Beckjord 2	7	236	1.58	100	KY	1974
150	W. C. Beckjord 3	8	237	1.58	125	KY	1973
638	C. R. Huntley 63	9	246	1.60	100		1973
639	C. R. Huntley 64	10	246	1.60	100		1973
640	C. R. Huntley 65	11	246	1.60	100		1973
641	C. R. Huntley 66	12	246	1.60	100		1973
15	Gadsden New 1	13	250	1.73	60	AL	1975
16	Gadsden New 2	14	250	1.73	60	AL	1975
346	Bowen 1	15	247	1.80	700	KY	1975
443	H. T. Pritchard 3	16	229	2.03	50	IN	1974
765	Shawville 3	17	229	2.04	188		
766	Shawville 4	18	229	2.04	188		
816	Gibson 1	19	246	2.70	668	IN, KY, IL	1976
817	Gibson 2	20	246	2.70	668	IN, KY, IL	1975

225 < SCA < 250. SUM OF MW - 7350

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
168	East Lake 5	21	230	2.71	680		
415	Baldwin 3	22	247	2.91	634	IL	1975
420	Vermillion 2	23	229	2.94	109	IL	1974
688	Toronto 5	24	238	2.99	44	OH	1980
561	Mill Creek (KY) 4	25	232	3.50	530	KY	1982
116	Coffeen 1	26	228	3.70	389	IL	

250 < SCA < 275. SUM OF MW - 8941

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
8	Barry 4	1	267	0.92	350	AL, TN	1976
242	J. M. Stuart 1	2	259	1.10	610	KY, OH, WV	1971
243	J. M. Stuart 2	3	259	1.10	610	KY, OH, WV	1970
244	J. M. Stuart 3	4	259	1.10	610	KY, OH, WV	1972
245	J. M. Stuart 4	5	259	1.10	610	KY, OH, WV	1974
301	Marshall 2	6	262	1.11	650	KY, VA	
302	Marshall 3	7	262	1.11	650	KY, VA	
146	Miami Fort 7	8	272	1.56	512	KY, OH	1975
353	Hammond 4	9	272	1.70	500	KY, TN, IL	1969
342	Arkwright 1	10	253	1.80	40	TN	1975
442	E. W. Stout 7	11	261	1.85	471	IN	1981
814	Edwardsport 7	12	252	2.04	36	IN, IL	1973
815	Edwardsport 8	13	252	2.04	36	IN, IL	
818	Gibson 3	14	252	2.70	668	IN, KY, IL	1978
819	Gibson 4	15	252	2.70	668	IN, KY, IL	1979
777	Bruce Mansfield 3	16	252	3.06	835	OH, PA	1980
706	Kyger Creek 1	17	265	3.73	217	OH, WV	1980
707	Kyger Creek 2	18	265	3.73	217	OH, WV	1980
708	Kyger Creek 3	19	265	3.73	217	OH, WV	1980
709	Kyger Creek 4	20	265	3.73	217	OH, WV	1980
710	Kyger Creek 5	21	265	3.73	217	OH, WV	1980

275 < SCA < 300. SUM OF MW - 5278

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
97	Cape Fear 5	1	297	1.01	141		
354	Harllee Branch 1	2	290	1.13	250	TN, KY	
355	Harllee Branch 2	3	298	1.13	319	TN, KY	
775	Sunbury 3	4	292	1.50	104	PA	

275 < SCA < 300, SUM OF MW = 5278

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
1045	Mount Storm 2	5	276	1.80	570	MINE MTH	
343	Arkwright 2	6	298	1.80	40	TN	1975
344	Arkwright 3	7	298	1.80	40	TN	1973
345	Arkwright 4	8	298	1.80	40	TN	1975
1044	Mount Storm 1	9	300	1.80	570	MINE MTH	
14	E. C. Gaston 5	10	287	1.83	880	AL, TN	1974
767	Warren 1	11	300	1.89	42		
768	Warren 2	12	300	1.89	42		
358	Jack McDonough 1	13	290	1.91	245	KY	1972
359	Jack McDonough 2	14	290	1.91	245	KY	1972
769	Brunner Island 2	15	284	2.00	405	PA	1976
771	Martins Creek 1	16	300	2.20	156	PA	
772	Martins Creek 2	17	300	2.20	156	PA	
125	Newton 1	18	289	2.70	617	IL	1977
129	Duck Creek 1	19	291	3.54	416	IL	1976

300 < SCA < 325, SUM OF MW = 6545

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
39	Kanawha River 1	1	315	0.74	220		1969
40	Kanawha River 2	2	315	0.74	220		1969
283	Belews Creek 1	3	305	0.85	1080	KY	1974
284	Belews Creek 2	4	305	0.85	1080	KY	1975
776	Sunbury 4	5	301	1.50	156	PA	
99	H. B. Robinson 1	6	323	1.54	207		
147	Miami Fort 8	7	323	1.56	512	KY, WV	1978
778	New Castle 1	8	320	1.57	43	PA	
779	New Castle 2	9	320	1.57	43	PA	
780	New Castle 3	10	320	1.57	103	PA	
781	New Castle 4	11	320	1.57	105	PA	
782	New Castle 5	12	320	1.57	132	PA	
151	W. C. Beckjord 4	13	306	1.58	165	KY	1975
890	Winyah 2	14	323	1.58	315	KY	1977
374	Yates 6	15	324	1.90	350	KY	1974
375	Yates 7	16	324	1.90	350	KY	1974
207	BC Cobb 1	17	307	2.30	66	WV, VA	
208	BC Cobb 2	18	307	2.30	66	WV, VA	
209	BC Cobb 3	19	307	2.30	66	WV, VA	
588	Jack Watson 4	20	307	2.58	299	IL, AL	1968
465	M. L. Kapp 2	21	324	2.60	218		

300 < SCA < 325, SUM OF MW = 6545

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
482	Riverside 4	22	317	2.66	43	IL	
481	Riverside 3	23	322	2.66	30	IL	
105	Roxboro 1	24	320	2.75	411	WV, VA, KY	1974
898	A. B. Brown 1	25	323	3.53	265	IN	1985

325 < SCA < 350, SUM OF MW = 6001

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
98	Cape Fear 6	1	330	1.01	188		
112	Weatherspoon 1	2	339	1.08	46	WV, VA, KY	1977
113	Weatherspoon 2	3	339	1.08	46	WV, VA, KY	1975
145	Miami Fort 6	4	333	1.56	168	KY	1976
889	Winyah 1	5	343	1.58	315	KY	1974
891	Winyah 3	6	346	1.58	315	KY	1980
347	Bowen 2	7	347	1.70	700	KY	
1065	Oak Creek 5	8	336	2.10	275	KY, IL, CO	
1066	Oak Creek 6	9	336	2.10	275	KY, IL, CO	
938	Colbert 5	10	326	2.30	550	OH	
58	B. L. England 2	11	349	2.70	163		1982
927	Big Bend 1	12	336	2.80	446	KY	
195	Kincaid 1	13	327	3.48	660	MINE MTH	1981
196	Kincaid 2	14	327	3.48	660	MINE MTH	1981
914	James River 3	15	330	3.90	44	KS	1979
970	Paradise 3	16	345	4.20	1150	KY	1969

350 < SCA < 375, SUM OF MW = 4454

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
519	Techumseh 9	1	351	0.54	82		1977
144	Miami Fort 5	2	353	1.56	100	KY, WV	1977
152	W. C. Beckjord 5	3	365	1.58	240	KY, OH	1976
210	BC Cobb 4	4	373	2.30	156	IL, WV, VA	
211	BC Cobb 5	5	373	2.30	156	IL, WV, VA	
57	B. L. England 1	6	353	2.70	136		1962
928	Big Bend 2	7	356	2.80	446	KY	
866	Sikeston 1	8	370	3.00	235	IL	1981
940	Cumberland 2	9	374	3.40	1300	KY	
939	Cumberland 1	10	375	3.40	1300	KY	1981
55	Thomas Hill 2	11	361	4.60	303	MO	1979

APPENDIX A (Continued)

375 < SCA < 400, SUM OF MW = 1881

Code	Name of unit	#	SCA	%S	MW	Fuel source	ESP date
212	DE Karn 1	1	384	0.98	265	OH, WV, VA	1959
213	DE Karn 2	2	384	0.98	265	OH, WV, VA	1961
1012	Maramec 1	3	399	1.18	138	VA, IL	1981
1013	Maramec 2	4	399	1.18	138	VA, IL	1981
248	Indian River 3	5	395	1.40	177		
167	East Lake 4	6	381	2.71	208		
929	Big Bend 3	7	398	2.80	446	OK, KY, MO	
423	Blue Valley 1	8	376	3.90	25	MO, KS	1979
424	Blue Valley 2	9	376	3.90	25	MO, KS	1979
917	Southwest 1	10	391	3.90	194	KS	1976

APPENDIX B

QUALITY CONTROL EVALUATION REPORT

Introduction

No Quality Assurance Project Plan (QAPP) was prepared. Quality control practices adopted under previous EPA projects were followed, however, in the areas of research where such practices had been worked out in the past. Those policies are described in the paragraphs that follow. In the measurement of particle charge, however, as discussed in Section 4, no quality control procedures were available.

Operation of the Pilot-Scale Combustor (Section 6)

Coal and sorbent feed rates to the combustor were checked by weighing the amount of material discharged during a fixed time interval. The actual coal feed rate was found to be typically within 1% of the set point on the gravimetric feeder. Sorbent feed rates were slightly less dependable due to the smaller amount of material being fed.

The flow rate of combustion air to the combustor was monitored with orifice meters, and the flow rate of sorbent transport air was monitored with a rotameter. Both measurements were corrected for actual line temperature and pressure.

The flow of water used for humidification of the flue gas was measured with a Matheson rotameter. The rotameter was calibrated by weighing timed discharges at several different flow rates over the range of the instrument. As with the air flow rates, the water flow rate was used only to check the consistency of the primary variables of interest. In the case of humidification, these variables are the approach to saturation and the absolute temperature.

All chemical analyses of ash and sorbent samples were checked for accuracy by the use of NBS SRM fly ash (SRM No. 1633a) and limestone (SRM No. 1c). Accuracies on all elements were well within the data quality objectives. Precisions were checked by replicate analyses of an Eastern U. S. fly ash. All relative standard deviations (RSDs) were under 2.5% except for SO_3, which had an RSD of 12%. This exceeded the data quality objective from previous QAPPs of 9%, which was based on experience. This difference was not considered to be critical.

For the analysis of flue gas in the combustor, a stream of flue gas was drawn through an in-stack, porous stainless steel filter. The gas was then drawn through a dehumidifier, which reduced the dewpoint to the range 32-40 °F, and next through a second in-line filter, which ensured virtually complete removal of suspended fly ash. The gas was then distributed through switching valves to the individual analyzers:

Beckman Model 755 Paramagnetic, O_2

Beckman Model 864 Nondispersive Infrared, CO_2

DuPont Model 400 Ultraviolet, SO_2

Thermo Electron Model 10 Chemiluminescent, NO_x

Horiba Model PIR-2000 NDIR, CO

All instruments were kept in dependable service on the basis of regular calibrations with certified calibration gases. In general, the precision and accuracy of each instrument was found to be within the data quality objectives specified in previous QAPPs. Multipoint calibrations revealed excellent linearity in the instrument responses.

Electrical Resistivity of Solids (Section 7)

The investigation of electrical resistivity was, to a considerable degree, an effort specifically to achieve quality control in the measurement of this property of the solids of interest. In other words, there was considerable emphasis on quality control per se, in addition to the emphasis on establishing a body of resistivity data. Experience with the type of solids of interest — that is, mixtures of fly ash and sorbent resulting from either furnace or duct injection of limestone or hydrated lime for SO_2 control — showed that the experimental procedures that had become routine with ordinary samples of fly ash did not produce reliable data. Effort was thus required to develop new procedures that would cope with the unusual properties of ash-sorbent mixtures.

The aspect of the procedure used to obtain resistivity data that required particular attention with respect to ash-sorbent mixtures was the direction in which temperature was changed (ascending or descending) to obtain the resistivity-temperature relationship. Another related feature of the measurement procedure was the maximum temperature that could be reached without causing an irreversible change in sample composition. The conclusions reached with regard to temperature control and variation are discussed in Section 7 of the body of this report.

Other aspects of the measurement procedure were dealt with in a more conventional manner, based upon the experience accumulated over a number of years of laboratory measurement of ash resistivity. The steps taken routinely to ensure data quality included the following:

- Measurements were made periodically of the resistivity of a sample of fly ash that was obtained at Alabama Power's E. G. Gaston power plant at Wilsonville, AL. The data thus obtained were compared with similar data from the past for the same material. The comparison demonstrated that measurements from the recent work were consistent with the measurements from prior work. There is no material serving generally in this and other laboratories as a resistivity standard; the Wilsonville ash, however, serves as a standard within this particular laboratory.

- Measurements were made in replicate to permit the computation of reliable average resistivity values. Overall, the repeatability of measurements was within 20%, which was considered excellent for a task in which repeatability within a factor of 2 is considered acceptable.

- The temperature of a sample was determined by indirect comparison to the temperature of the oven in which the sample was maintained during measurement. The relationship between sample and oven temperatures was based on a set of temperature readings taken earlier with thermocouples placed in both the sample and the oven environment. A thermocouple could not be left in the sample during actual resistivity measurements for the obvious reason that it would produce a dominant alternate path for electrical current.

- The desired concentration of water vapor in the oven was achieved by passing air through a water bubbler at a controlled temperature and verifying the concentration by a gravimetric procedure. This procedure consisted of withdrawing air at a controlled rate (0.8 L/min) through a critical orifice and collecting the water vapor on a preweighed cartridge of Drierite.

- The sample resistivity was calculated from the electrical current produced at a fixed voltage and measured with a Keithley Model 610C electrometer. The electrometer was calibrated periodically by the manufacturer and checked routinely by determination of the current produced in a precision resistor.

Field Measurements of the E-SOX Process (Section 8)

The field measurements of the E-SOX process were performed at the Burger station.

Method 17. The total mass concentration of particulate matter suspended in the flue gases was determined by EPA Method 17. The procedures and equipment used in Method 17 are described in the Code of Federal Regulations, Title 40, Part 60, Appendix A, pp. 220-237 (July 1, 1978). The calibration procedures included in Method 17 were used to calibrate the equipment used in the field with the exception of the flow measurement devices. The flow measuring devices were calibrated with a Meriam Laminar Flow Element which is traceable to the National Bureau of Standards. During the E-SOx test program, the dry gas meters were also sent to Andersen Samplers for additional calibrations which are in accordance with the outlined procedures in Method 17.

Cascade Impactors. The size distribution of the baseline fly ash and the fly ash-sorbent particulate matter in the size range of 0.5 to 10 μm was determined with cascade impactors. The equipment used to determine flow, temperature, pressure, and stage weights were calibrated and checked as was the equipment for Method 17. Although there are no EPA regulations for cascade impactors, SRI has used the information developed under many EPA contracts regarding impactor operation as guidelines for obtaining the impactor data at the E-SOx facility. The Procedures Manual for the

Recommended ARB Particle Distribution Method (Cascade Impactors), which was prepared for the California Air Resources Board, contains the procedures and calibration methods which Southern Research Institute uses.

Resistivity. The resistivity of the fly ash and fly ash-sorbent mixtures were determined in situ by means of the SRI point-to-plane resistivity probe. The in situ resistivity probe cannot be calibrated in the traditional sense because standard particulate reference materials having a known resistivity when suspended in a known gaseous environment are not available.

Although a standard calibration procedure for an in situ resistivity probe is not available, a number of checks are made to ensure that the probe is operating properly. The probes electronics are checked with the spark protection box which has a switch to include a precision resistor (1×10^9 ohm) in the circuit. The power supply is set at a known voltage and the sliding electrode is lowered to a point where a known current should be displayed on the current meter. This resistance check also acts as a check on the electrical connections. The micrometer, used to determine the cell thickness in the resistivity calculation, is checked with materials of known thickness and precision calipers.